Measuring Masses and Spins of New Particles at Colliders!

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Hints for New Physics Beyond the Standard Model

- Dark Matter: 23% of the unknown in the universe
  - Best evidence for new physics beyond the Standard Model: if the dark matter is the thermal relic of a WIMP, its mass should be of the weak scale
  $$\Omega_{WIMP} \sim \left(\frac{1}{10^2\alpha}\right)^2 \left(\frac{M_{WIMP}}{1\ TeV}\right)^2$$
  - Requires a stable (electrically) neutral weakly interacting particle at $\mathcal{O}(1)$ TeV
  - To be stable, it should be the lightest particle charged under a new symmetry
- Electroweak precision measurements
  - There is no evidence of deviations of the EW observables from the SM predictions
  - New physics contributions to the EW observables should be suppressed
  - Possible if new particles are charged under a new symmetry under which SM is neutral
  - Their contributions will be loop-suppressed and the lightest particle is stable

$\Rightarrow$ Collider implications:
  - Pair production of new particles
  - Cascade decays down to the lightest particle give rise to missing energy plus jets/leptons

"Confusion scenario"

- What is new physics if we see jets/leptons + missing energy at the colliders?

- The standard answer: Supersymmetry with R-parity
$\rightarrow$ for a long time, this was the only candidate

- From the above discussion, we see that any new physics satisfying hints we have may show up at the LHC with similar signals

- Michael Peskin's name for different kinds of new heavy particles whose decay chains result in the same final state (copied from Joe's slide, 'Is Particle Physics Ready for the LHC?')

- How can we discriminate SUSY from confusion scenarios?

- How do we know new physics is SUSY?

Outline

- New physics beyond the SM is expected to be discovered at the LHC but will we know what it is?
  - Example: Universal Extra Dimensions (5D)
  - Relic Density of KK Dark Matter and Direct Detection Limit
  - Collider Phenomenology of UEDs: Spin Determination
- Mass Measurements: bump, edges in cascade decay, m_T, $m_{T2} \cdots$
- Spin and Mass measurement at LC
- Summary

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu, hep-ph/0012100)

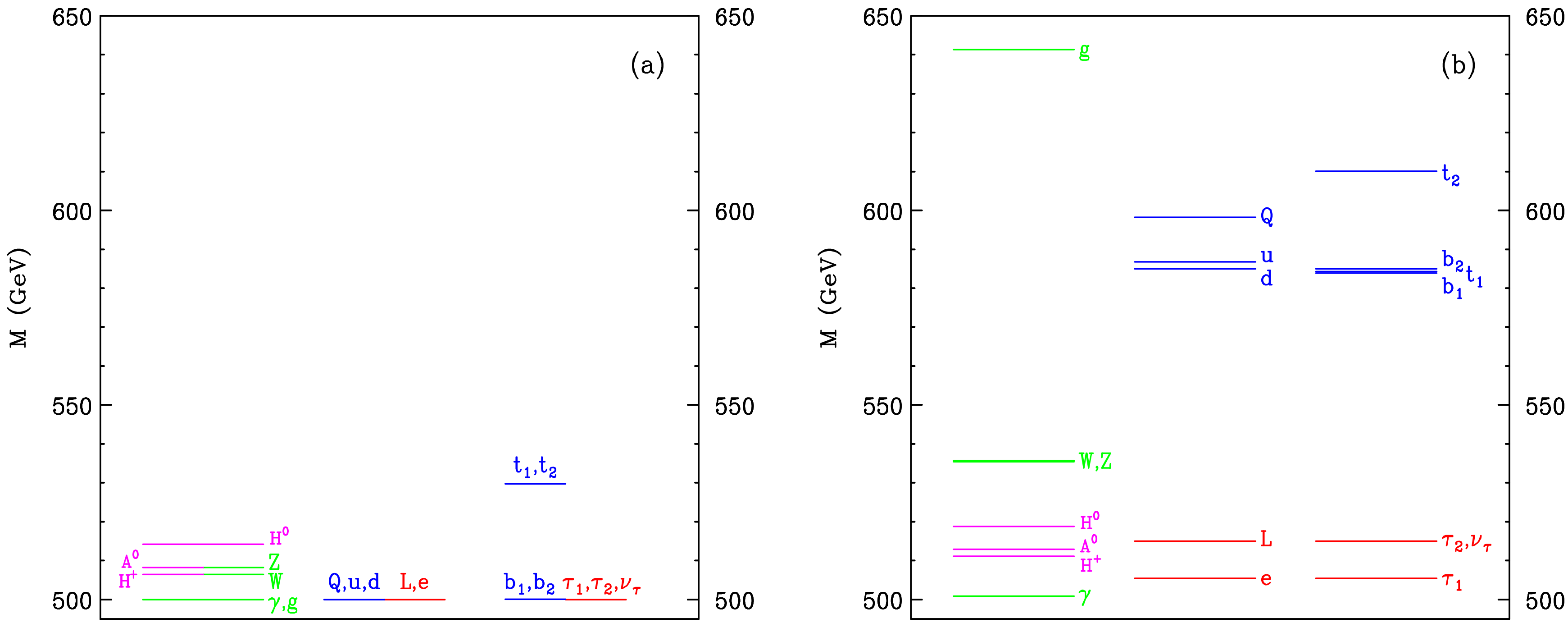
- Each SM particle has an infinite number of KK partners
  - The number of KK states $= \Lambda R$ (Λ is a cut-off)
- KK particle has the same spin as SM particle with a mass, $\sqrt{\frac{n^2}{R^2} + m^2}$
  - SM particles became massive through electroweak symmetry breaking
  - KK gauge bosons get masses by eating 5th components of gauge fields (Nambu-Goldstone bosons) and EWSB shifts those masses
- All vertices at tree level satisfy KK number conservation

$$|m \pm n \pm k| = 0 \text{ or } |m \pm n \pm k \pm l| = 0$$

- KK number conservation is broken down to KK-parity, $(-1)^n$, at the loop level
  - The lightest KK partner at level 1 (LKP) is stable $\Rightarrow$ DM ?
  - KK particles at level 1 are pair-produced
  - KK particles at level 2 can be singly produced
  - Additional allowed decays: $2 \to 00$, $3 \to 10$, $\cdots$
  - No tree-level contributions to precision EW observables
- New vertices are the same as SM interactions
  - Couplings between SM and KK particles are the same as SM couplings
  - Couplings among KK particles have different normalization factors
- There are two Dirac (KK) partners at each level n for one Dirac fermion in SM

Mass Spectrum : Tree level and radiative corrections

(Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)



- Tree level mass $m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2}$, e_1 is stable $\cdots$
- Radiative corrections are important !
- All but LKP decay promptly $\longrightarrow$ missing energy signals

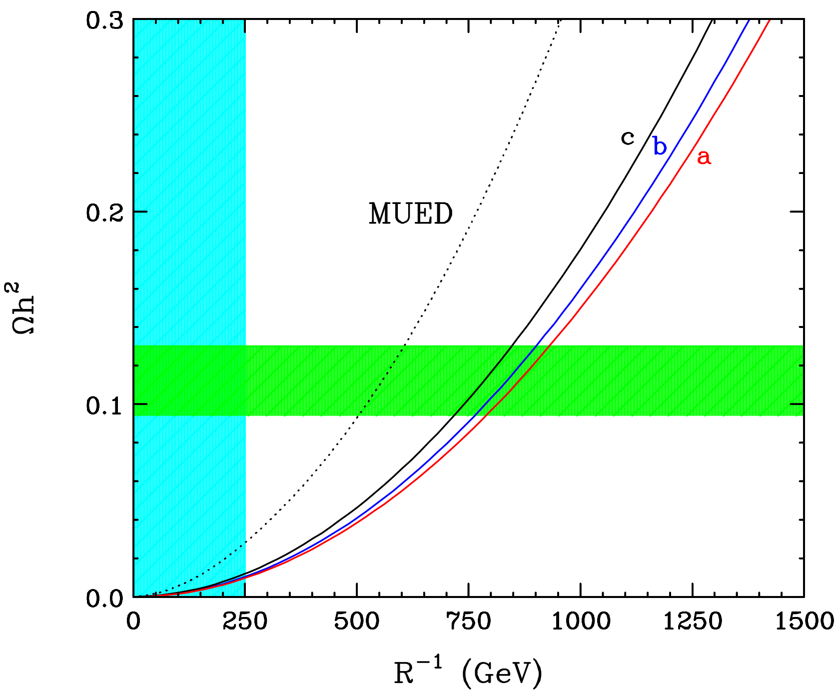
Relic Density Code

- Kong and Matchev (UF, 2005)
  - Fortran
  - Includes *all* level 1 KK particles
  - has a general KK mass spectra (all KK masses are, in principle, different)
  - can deal with different types of KK dark matter (γ_1, Z_1, $\nu_1 \cdots$)
  - improved numerical precision
    - use correct non-relativistic velocity expansion ($\langle \sigma v \rangle = a + b\langle v^2 \rangle$)
    - use temperature dependent degrees of freedom ($g_* = g_*(T_F)$)
- Servant and Tait (Annecy/ANL, 2002)
  - First code (γ_1 or ν_1 dark matter)
  - has cross sections in Mathematica, assuming same KK masses
  - use approximate non-relativistic velocity expansion
  - use approximate degrees of freedom ($g_* = 92.25$)
- Kribs and Burnell (Oregon/Princeton, 2005)
  - has cross sections in Maple, assuming same KK masses (γ_1 dark matter)
  - do not use non-relativistic velocity expansion
  - deal with coannihilations with all level 1 KK
- Kakizaki, Matsumoto and Senami (Bonn/KEK/Tokyo, 2006)
  - interested in resonance effects (γ_1 dark matter)

Improved result

(Kong, Matchev, hep-ph/0509119)

- Improvements in our calculation:
  - Include all coannihilations: many processes (51×51 initial states)
  - Keep KK masses different in the cross sections:
  - Use temperature dependent g_*
  - Use relativistic correction in the b-term

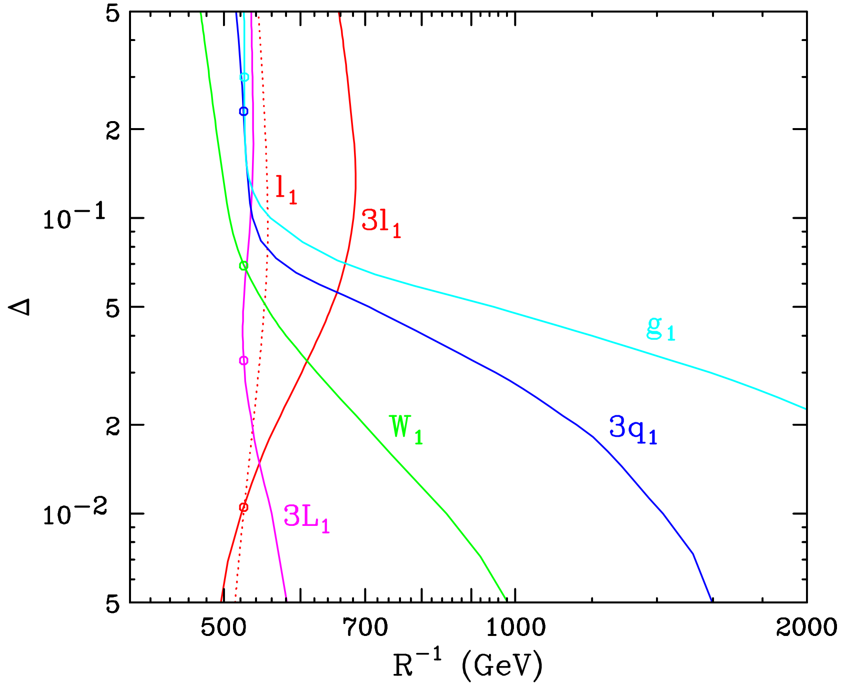


- a: $\gamma_1\gamma_1$ annihilation only (from hep-ph/0206071)
- b: repeats the same analysis but uses temperature dependent g_* and relativistic correction
- c: relaxes the assumption of KK mass degeneracy
- MUED: full calculation in MUED including all coannihilations with the proper choice of masses
- Preferred mass range: $500 - 600$ GeV for $0.094 < \Omega_{CDM} h^2 < 0.129$

Dark matter in nonminimal UED

- The change in the cosmologically preferred value for R^{-1} as a result of varying the different KK masses away from their nominal MUED values (along each line, $\Omega h^2 = 0.1$)

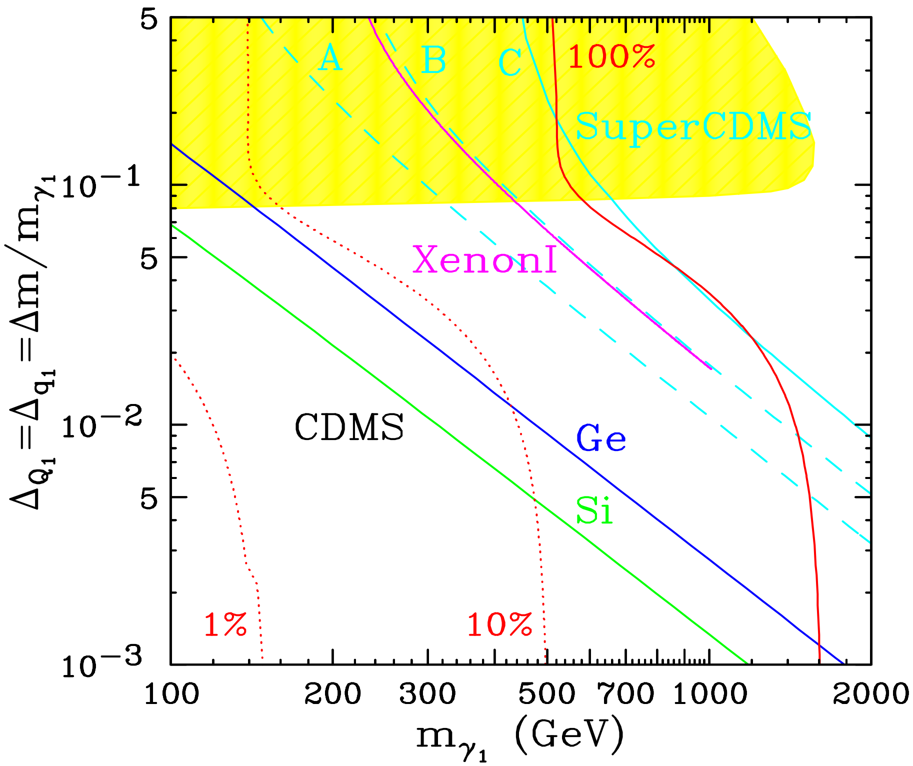
(Kong, Matchev, hep-ph/0509119)

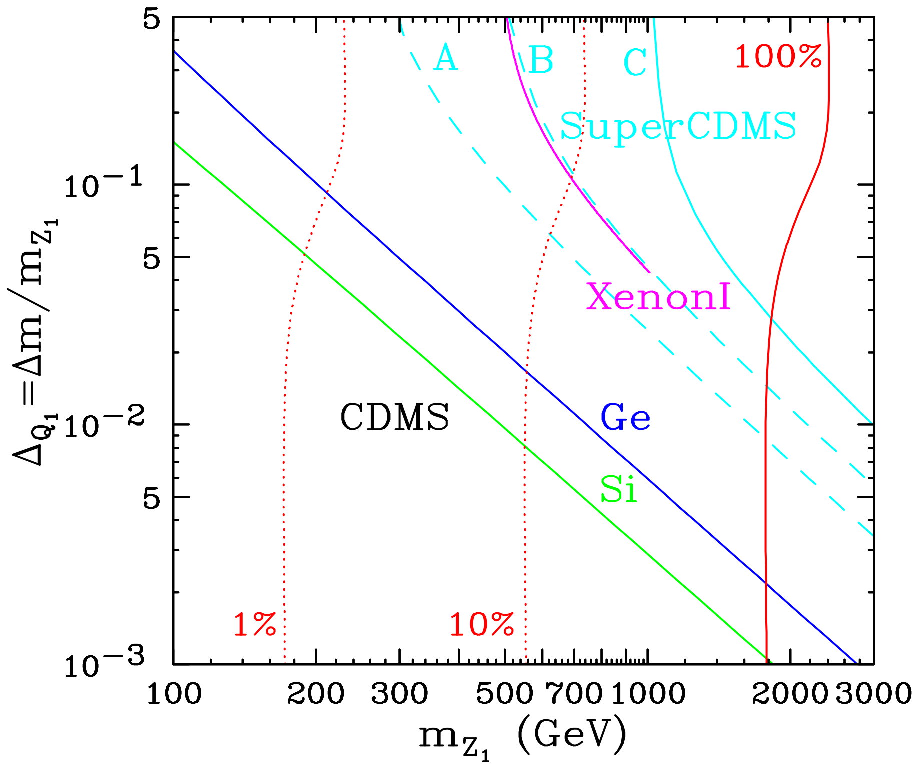


- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, m_{LKP} is large, UED escapes collider searches
    $\longrightarrow$ But, good news for dark matter searches

CDMS (Spin independent): B_1 and Z_1 LKP

(Baudis, Kong, Matchev, Preliminary)

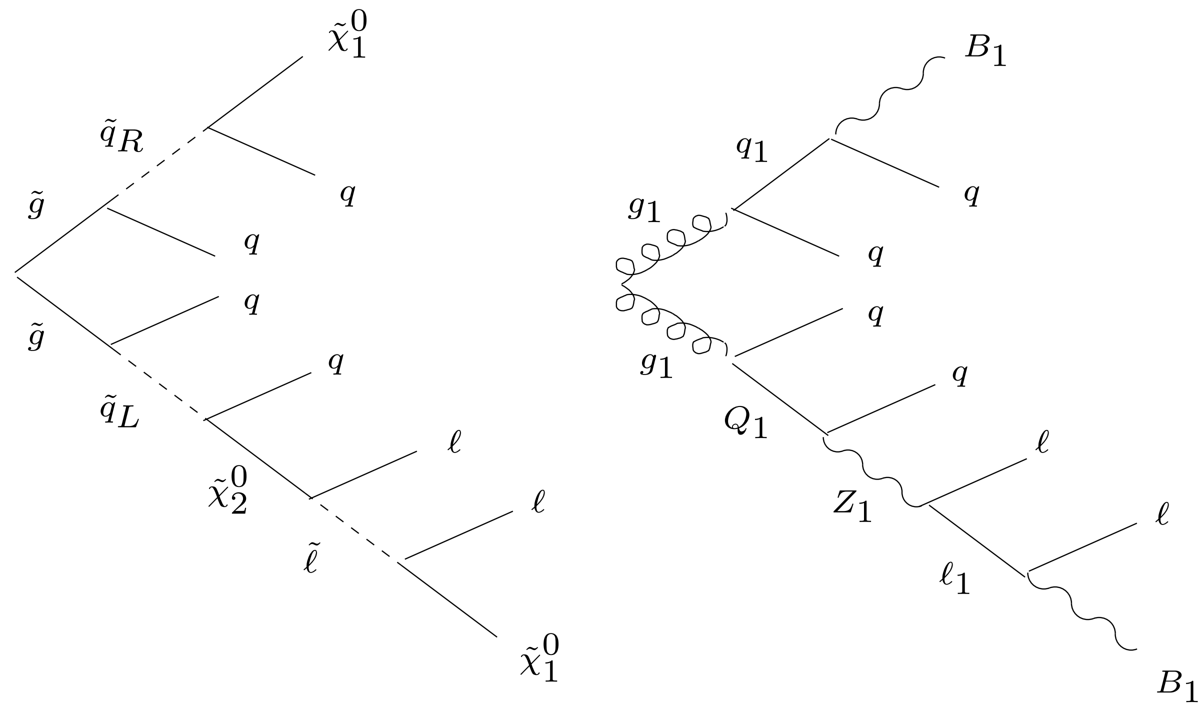




- SuperCDMS (projected)
  - A (25 kg), B (150 kg), C (1 ton)
- $\Delta_{q_1} = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$

- Z_1 LKP in nonminimal UED:
  - $\Delta_{Q_1} = \frac{m_{Q_1} - m_{Z_1}}{m_{Z_1}}$
  - $\Delta_{g_1} = 0.2$
  - $\Delta_1 = 0.1$

Typical event in SUSY and UED



- Both have similar diagrams $\longrightarrow$ same signatures!
  - At first sight, it is not clear which model we are considering
- The decay chain is complicated
- A lot of jets $\longrightarrow$ correct jet identification is difficult $\longrightarrow$ ISR/FSR add more confusion
- UED discovery reach at the Tevatron and LHC: (Cheng, Matchev, Schmaltz, hep-ph/0205314)
  - Reach at the LHC: $R^{-1} \sim 1.5$ TeV with 100 fb^{-1} in $4l + \not{E}_T$ channel
  - UED search by CMS group (full detector simulation)

How to discriminate:

- Level 1 just looks like MSSM with LSP dark matter:

  (Cheng, Matchev, Schmaltz, hep-ph/0205314)

- Can we discriminate SUSY from UED ?

	SUSY	UED
How many new particles	1^*	KK tower
Spin of new particles	differ by $\frac{1}{2}$	same spins
Couplings of new particles	same as SM	same** as SM
Masses	SUSY breaking	boundary terms
Discrete symmetry	R-parity	KK-parity $= (-1)^n$
Dark matter	LSP $(\tilde{\chi}_1^0)$	LKP (γ_1)
Generic signature***	$\not{E}_T$	$\not{E}_T$

* $N = 1$ SUSY

** Couplings among some KK particles may have factors of $\sqrt{2}$, $\sqrt{3}$, $\cdots$

*** with dark matter candidates

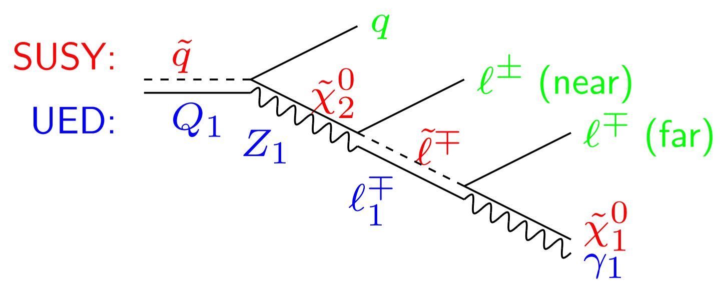
- Finding KK tower: Datta, Kong, Matchev, hep-ph/0509246
- Spin measurements: Barr, hep-ph/0405052
  Smillie, Webber hep-ph/0507170
  Datta, Kong, Matchev, hep-ph/0509246
- Cross section: Datta, Kane, Toharia, hep-ph/0510204

Implementation of UED in Event Generators

- Datta, Kong and Matchev (UF, 2004)
  - Full implementation of level 1 and level 2 in `CompHEP/CalcHEP` (spin information)
  - Provided for implementation in `PYTHIA`
  - Two different mass spectrum possible:
    * A general mass spectrum in Nonminimal UED
    * All masses/widths calculated automatically in Minimal UED
  - Used for dark matter study/collider studies
  - Used for ATLAS and CMS ($4\ell + \not{E}_T$, $nj + m\ell + \not{E}_T \cdots$)
- Alexandre Alves, Oscar Eboli, Tilman Plehn (2006)
  - Level 1 QCD and decays only in `MADGRAPH` (spin information!)
- Wang and Yavin (Harvard, 2006)
  - Level 1 QCD and decays only in `HERWIG` (full spin information)
- Smillie and Webber (Cambridge, 2005)
  - Level 1 QCD and decays only in `HERWIG` (full spin information)
- Peskin (Stanford, in progress)
  - Level 1 QCD and decays only in `PANDORA` (full spin information)
- El Kacimi, Goujdami and Przysiezniak (2005)
  - Level 1 QCD and decays only in `PYTHIA` (spin information is lost)
  - Matrix elements from `CompHEP/CalcHEP`

Spin measurement

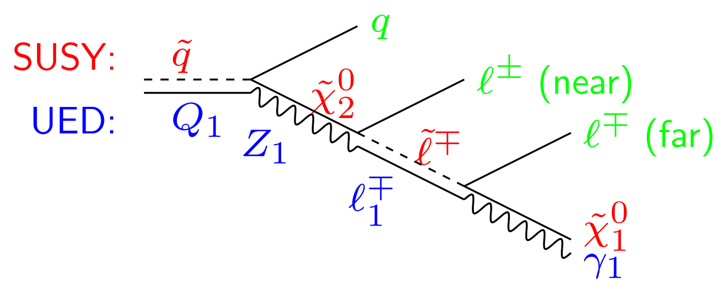
- spin measurement is difficult
  - LSP/LKP is neutral $\longrightarrow$ missing energy
  - There are two LSPs/LKPs $\Rightarrow$ cannot find CM frame
  - Decay chains are complicated $\longrightarrow$ cannot uniquely identify subchains
  - Look for something easy : look for 2 SFOS leptons, $\tilde{\chi}_2^0 \longrightarrow \tilde{\ell}^{\pm}\ell^{\mp} \longrightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ or $Z_1 \longrightarrow \ell\ell_L^1 \longrightarrow \ell^+\ell^-\gamma_1$
  - Dominant source of $\tilde{\chi}_2^0/Z_1$: squark/KK-quark decay $\tilde{q} \longrightarrow q\tilde{\chi}_2^0 \longrightarrow q\tilde{\ell}^{\pm}\ell^{\mp} \longrightarrow q\ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ or $Q_1 \longrightarrow qZ_1 \longrightarrow \ell\ell_L^1 \longrightarrow \ell^+\ell^-\gamma_1$:



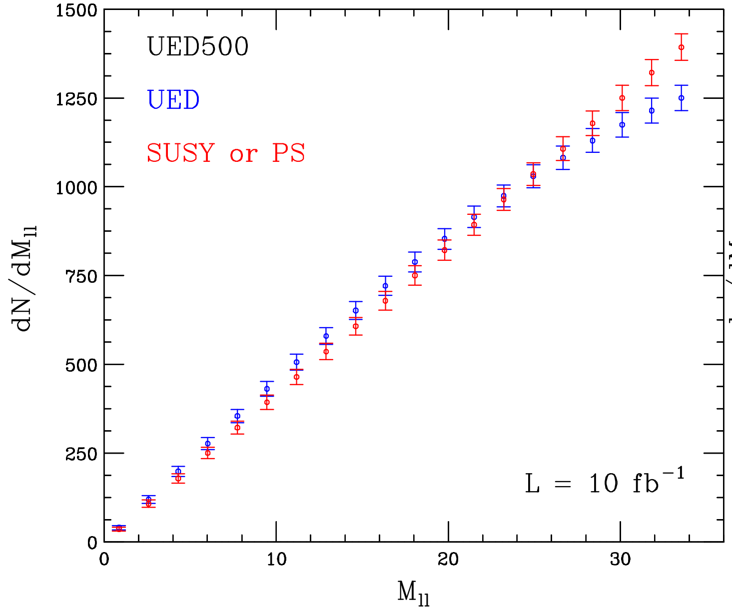
- Study this chain: Observable objects are q and $\ell^{\pm}$
- Can do: $M_{\ell^+\ell^-}$, $M_{q\ell^-}$ and $M_{q\ell^+}$ where $M_{ab}^2 = (p_a - p_b)^2$
- Which jet? Which lepton? Charge of jets (q and $\bar{q}$)?
  - $M_{\ell^+\ell^-}$, Asymmetry $= A^{+-} = \dfrac{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} - \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}{\left(\frac{d\sigma}{dm}\right)_{q\ell^+} + \left(\frac{d\sigma}{dm}\right)_{q\ell^-}}$ (Barr,Phys.Lett.B596:205-212,2004)
- Masses don't discriminate

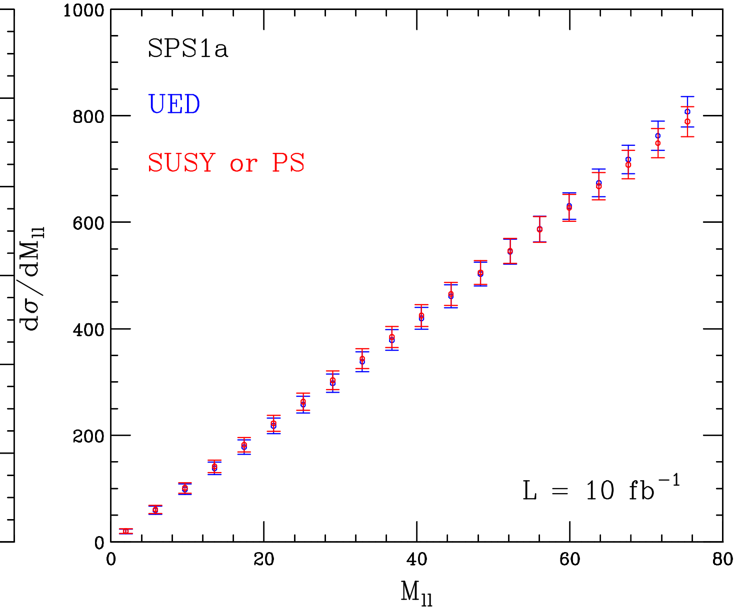
Dilepton distribution

- Look for spin correlations in $M_{\ell^+\ell^-}$
- Choose a study point in one model and fake mass spectrum in the other model



(Kong, Matchev Preliminary and Smillie, Webber hep-ph/0507170)





- Why are they the same ?

Dilepton distribution

- How do we fake the $M_{\ell^+\ell^-}$ distribution ?

(Smillie, Webber hep-ph/0507170)

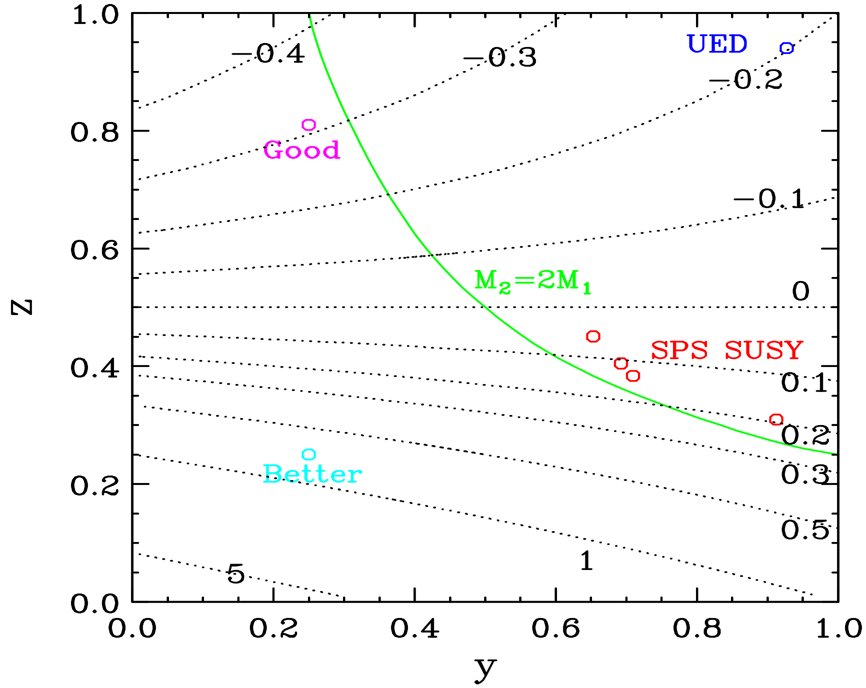
Phase Space : $\frac{dN}{d\hat{m}} = 2\hat{m}$

SUSY : $\frac{dN}{d\hat{m}} = 2\hat{m}$

UED : $\frac{dN}{d\hat{m}} = \frac{4(y+4z)}{(1+2z)(2+y)} \left(\hat{m} + r\,\hat{m}^3\right)$

$$r = \frac{(2-y)(1-2z)}{y+4z}$$

(Kong, Matchev Preliminary)



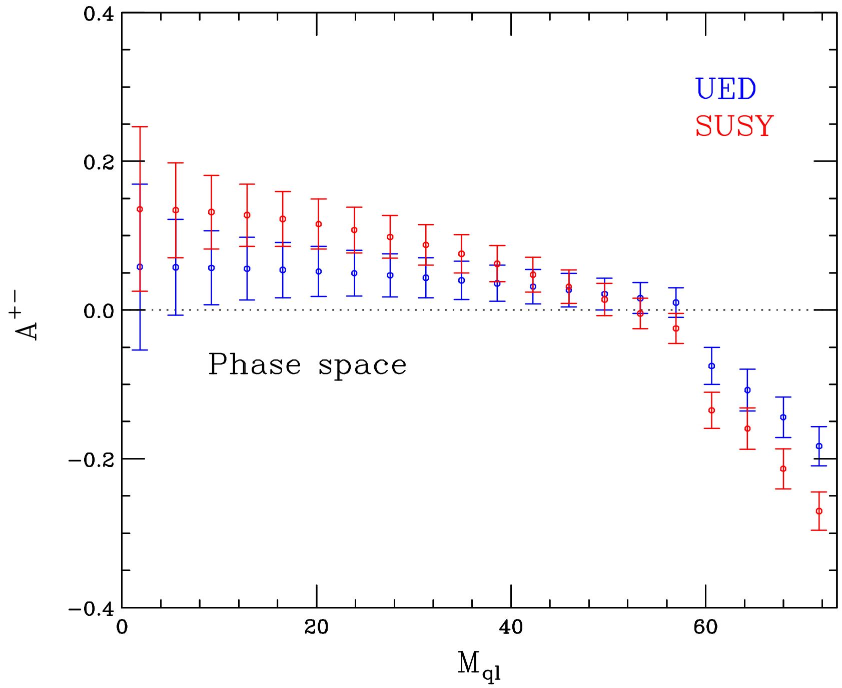
where $\hat{m} = \frac{m_{\ell\ell}}{m_{\ell\ell}^{max}}$, $y = \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2$ and $z = \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2$

- $|r| \le 0.4$ in mSUGRA

Asymmetry

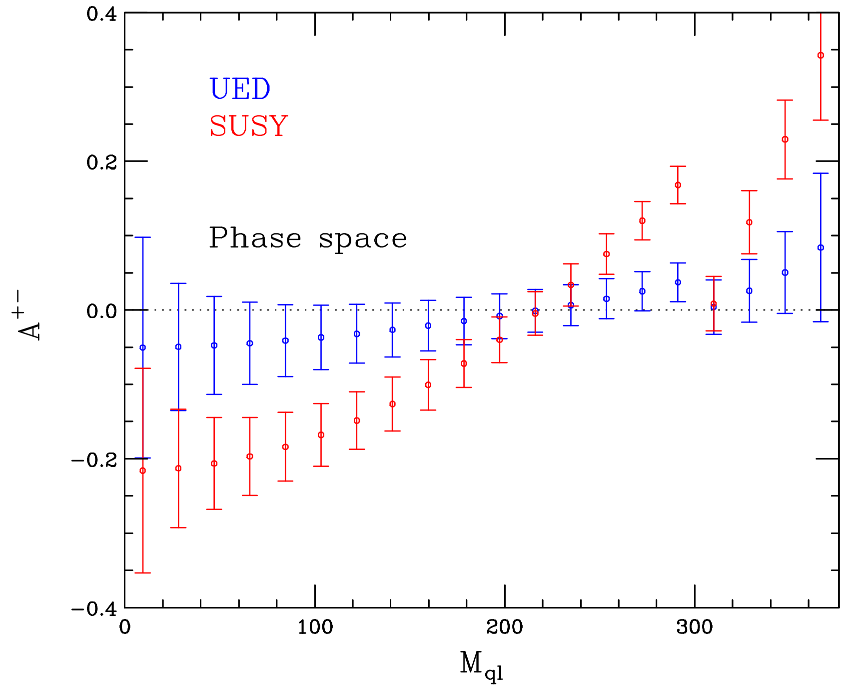
- Asymmetry with UED500 mass spectrum $(\mathcal{L} = 10\mathrm{fb}^{-1})$

(Datta, Kong, Matchev, hep-ph/0509246)



- Asymmetry with SPS1a mass spectrum $(\mathcal{L} = 10\mathrm{fb}^{-1})$

(Kong, Matchev Preliminary)

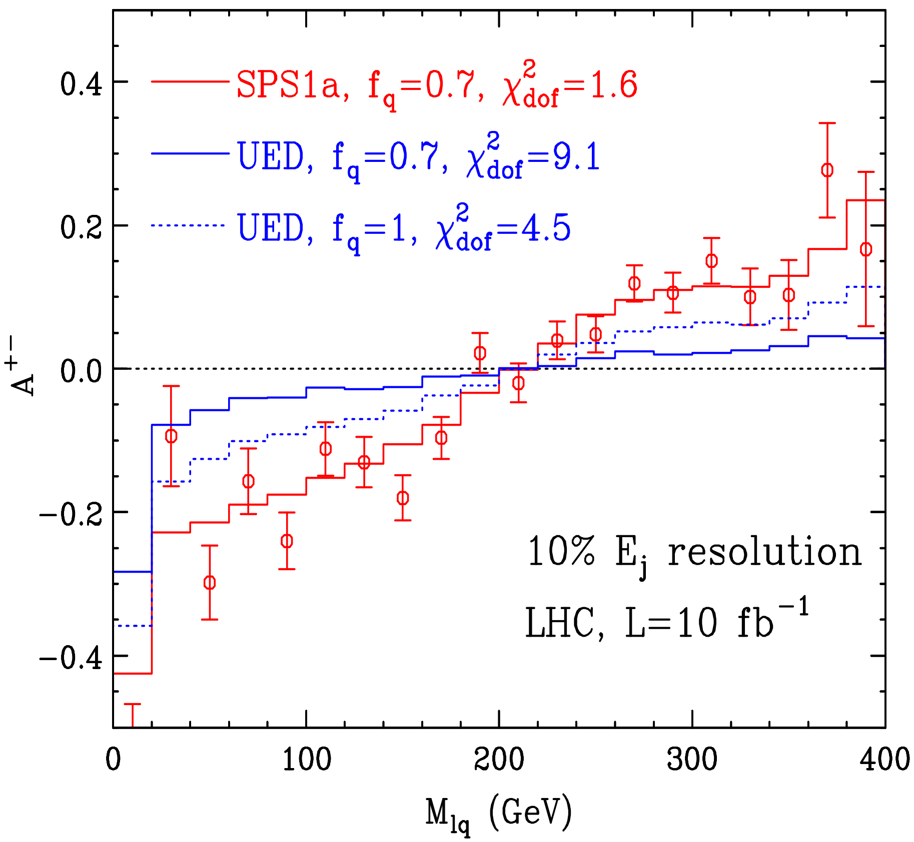


$$Z_1 \to \ell \ell^1_L \to \ell^+ \ell^- \gamma_1 \qquad \text{Chirality} \qquad Z_1 \to \ell \ell^1_R \to \ell^+ \ell^- \gamma_1$$

$$\tilde{\chi}^0_2 \to \ell \tilde{\ell}_L \to \ell^+ \ell^- \tilde{\chi}^0_1 \qquad \Longleftrightarrow \qquad \tilde{\chi}^0_2 \to \ell \tilde{\ell}_R \to \ell^+ \ell^- \tilde{\chi}^0_1$$

SPS1a mSUGRA point

(Kong, Matchev Preliminary)

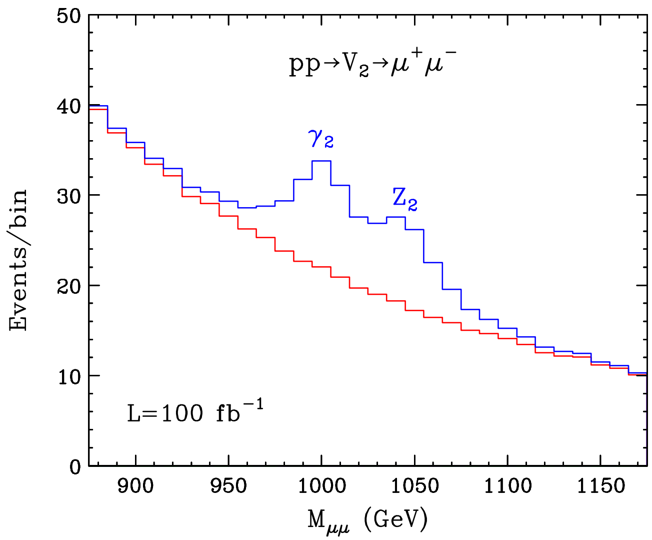


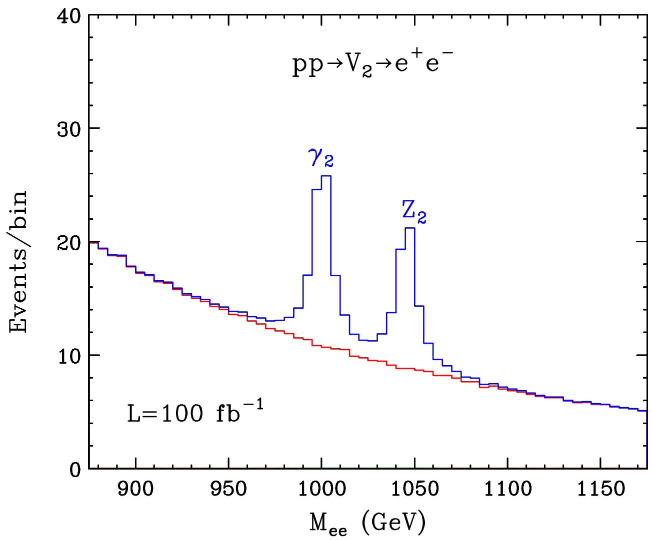
- How to fake SPS1a asymmetry
  - five parameters in asymmetry : f_q, x, y, z, $m_{\tilde{q}}$
  - three kinematic endpoints : m_{qll}, m_{ql} and m_{ll}
    - $m_{qll} = m_{\tilde{q}}\sqrt{(1-x)(1-yz)}$
    - $m_{ql} = m_{\tilde{q}}\sqrt{(1-x)(1-z)}$
    - $m_{ll} = m_{\tilde{q}}\sqrt{x(1-y)(1-z)}$
  - two parameters left : f_q, x
  - minimize χ^2 in the $(x,\ f_q)$ parameter space
  - minimum χ^2 when UED and SUSY masses are the same and $f_q \approx 1$
- 10% jet energy resolution + statistical error $\rightarrow \chi^2$ better but not enough to fake SPS1a in UED
- effect of wrong jets $\rightarrow$ asymmetry smaller ? Flavor subtraction? (work in progress)

$$x = \left(\frac{m_{\tilde{\chi}^0_2}}{m_{\tilde{q}}}\right)^2,\ y = \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}^0_2}}\right)^2,\ z = \left(\frac{m_{\tilde{\chi}^0_1}}{m_{\tilde{\ell}}}\right)^2,\ f_q = \frac{N_q}{N_q+N_{\tilde{q}}},\ f_{\bar{q}} = \frac{N_{\tilde{q}}}{N_q+N_{\tilde{q}}},\ f_q+f_{\bar{q}} = 1$$

How do we measure masses?: bump hunting!

(Datta, Kong, Matchev, hep-ph/0509246)

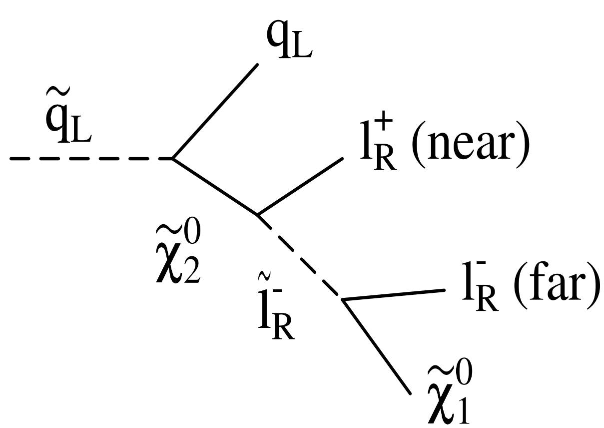




- Bump hunting!: ex. two resonances in UEDs
- Level 2 resonances can be seen at the LHC:
  - up to $R^{-1} \sim 1$ TeV for 100 fb^{-1}, $M_{ab}^2 = (p_a + p_b)^2$
  - covers dark matter region of MUED
- Mass resolution:
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV} \right)$ for $\mu^+\mu^-$
- Narrow peaks are smeared due to the mass resolution
- Two resonances can be better resolved in e^+e^- channel
- Is this a proof of UED ?
  - Not quite : resonances could still be interpreted as Z's
  - Smoking guns :
    - Their close degeneracy
    - $M_{V_2} \approx 2 M_{V_1}$
    - Mass measurement of $W_2^{\pm}$ KK mode
- However in nonminimal UED models, degenerate spectrum is not required $\longrightarrow$ just like SUSY with a bunch of Z's $\longrightarrow$ need spins to discriminate

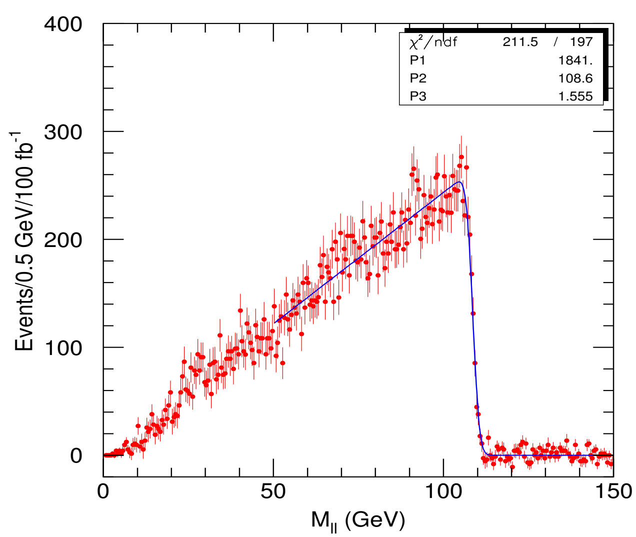
How do we measure masses?: cascade decays!

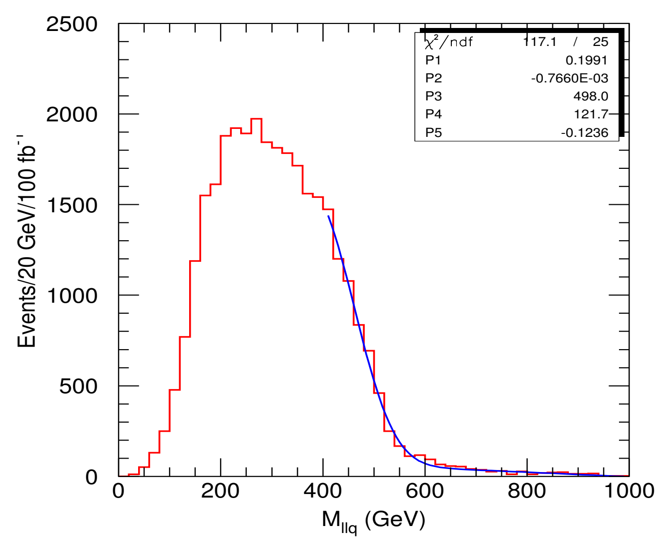
- Cascade decays! (Bachacou, Ian Hinchliffe, Paige, hep-ph/9907518)



$$M_{\ell\ell}^{max} = \sqrt{\frac{\left(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}_R}\right)\left(M^2_{\tilde{\ell}_R} - M^2_{\tilde{\chi}_1^0}\right)}{M^2_{\tilde{\ell}_R}}}$$

$$M_{q\ell\ell}^{max} = \sqrt{\frac{\left(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}_2^0}\right)\left(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\chi}_1^0}\right)}{M^2_{\tilde{\chi}_2^0}}}$$





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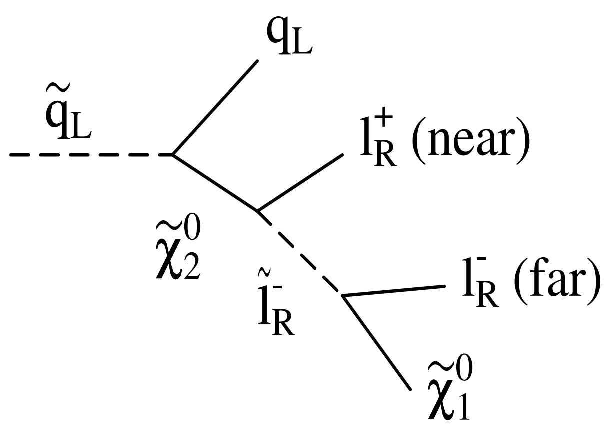
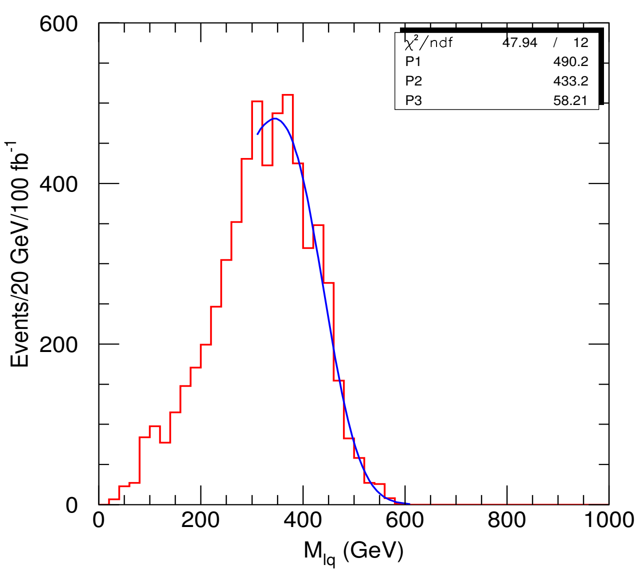
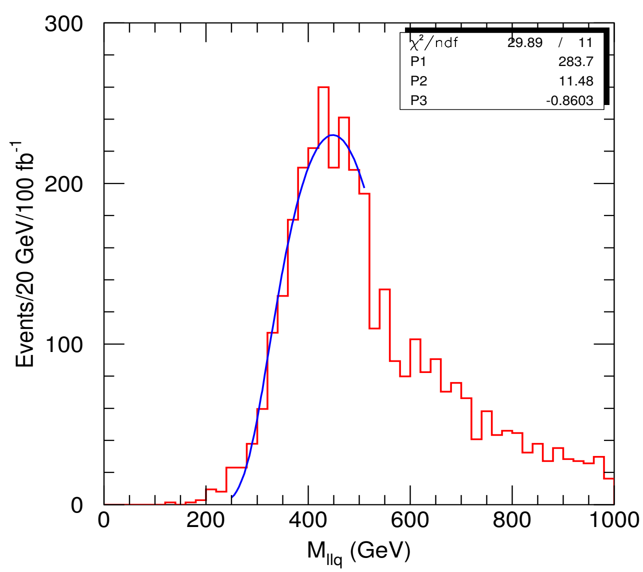


$$M_{q\ell}^{max} = \sqrt{\frac{\left(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2}\right)\left(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_R}\right)}{M^2_{\tilde{\chi}^0_2}}}$$

$M_{\ell\ell q}^{\min}$ with $M_{\ell\ell} > M_{\ell\ell}^{max}/\sqrt{2}$





How do we measure masses?: cascade decays!

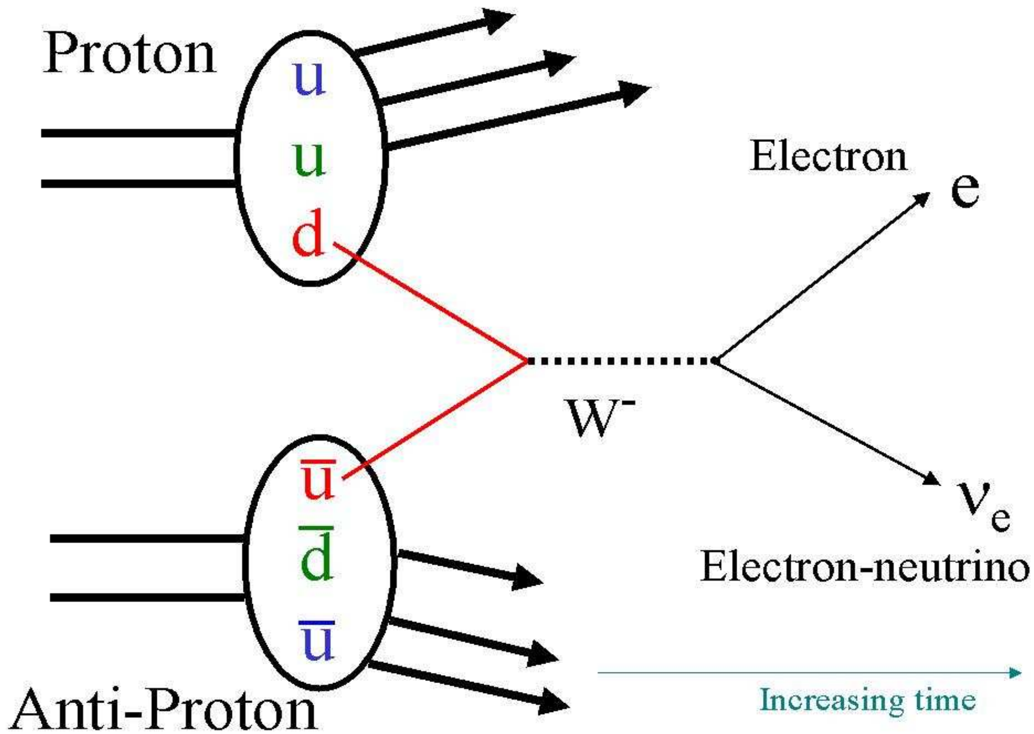
- Cascade decays! (Bachacou, Ian Hinchliffe, Paige, hep-ph/9907518)

$$
\begin{aligned}
(M_{\ell\ell q}^{\min})^2 \quad = \quad & \frac{1}{4M_2^2 M_e^2} \times \\
& \Big[-M_1^2 M_2^4 + 3M_1^2 M_2^2 M_e^2 - M_2^4 M_e^2 - M_2^2 M_e^4 - M_1^2 M_2^2 M_q^2 - \\
& M_1^2 M_e^2 M_q^2 + 3M_2^2 M_e^2 M_q^2 - M_e^4 M_q^2 + (M_2^2 - M_q^2) \times \\
& \sqrt{(M_1^4 + M_e^4)(M_2^2 + M_e^2)^2 + 2M_1^2 M_e^2 (M_2^4 - 6M_2^2 M_e^2 + M_e^4)} \Big]
\end{aligned}
$$

with $M_{\ell\ell} > M_{\ell\ell}^{max}/\sqrt{2}$

$M_1 = M_{\tilde{\chi}_1^0}$, $M_2 = M_{\tilde{\chi}_2^0}$, $M_e = M_{\tilde{\ell}_R}$ and $M_q = M_{\tilde{q}_L}$

How do we measure masses?: m_T



- m_T!

$$M_W^2 \geq m_T^2(e,\nu) \equiv (|\vec{p}_{eT}| + |\vec{p}_{\nu T}|)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2$$

What if there are two missing particles?: m_{T2}

(Barr, Lester, Stephens, hep-ph/0304226, "m(T2): The Truth behind the glamour")

(Lester, Summers, hep-ph/9906349)

$$
\begin{aligned}
m_{\tilde{\ell}}^2 &= m_{\tilde{\chi}_1^0}^2 + 2\left[E_T^{\ell} E_T^{\tilde{\chi}_1^0}\cosh\left(\Delta\eta\right) - \vec{p}_T^{\,\ell}\cdot\vec{p}_T^{\,\tilde{\chi}_1^0}\right] \\
E_T^{\ell} &= |p_T| \\
E_T^{\tilde{\chi}_1^0} &= \sqrt{\left(\vec{p}_T^{\,\tilde{\chi}_1^0}\right)^2 + m_{\tilde{\chi}_1^0}^2} \\
\eta &= \frac{1}{2}\log\left[\frac{E+p_z}{E-p_z}\right]
\end{aligned}
$$

($\tanh\eta = \frac{p_z}{E}$, $\sinh\eta = \frac{p_z}{E_T}$ and $\cosh\eta = \frac{E}{E_T}$)

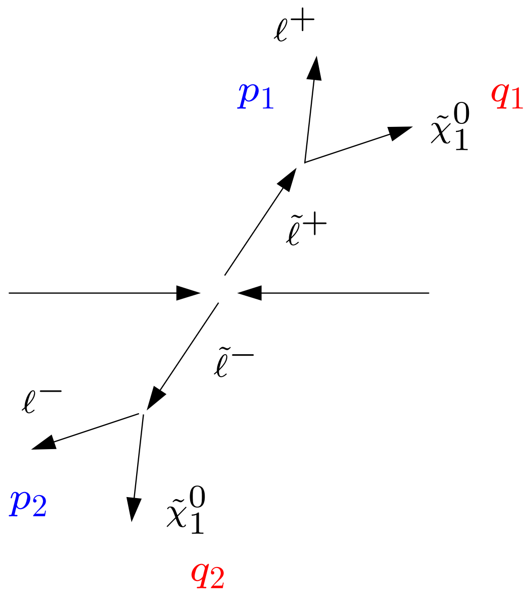
$$
\begin{aligned}
m_T^2(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^0}) &\equiv m_{\tilde{\chi}_1^0}^2 + 2\left(E_T^{\ell} E_T^{\tilde{\chi}_1^0} - \vec{p}_T^{\,\ell}\cdot\vec{p}_T^{\,\tilde{\chi}_1}\right) \\
m_T &\leq m_{\tilde{\ell}}
\end{aligned}
$$

- We don't measure $\vec{p}_T^{\,\tilde{\chi}_1^0}$
- Most of new physics have at least two missing particles in the final state

What if there are two missing particles?: m_{T2}

(Barr, Lester, Stephens, hep-ph/0304226, "m(T2): The Truth behind the glamour")

(Lester, Summers, hep-ph/9906349)



- $\not{E}_T = \vec{q}_1 + \vec{q}_2 = -(\vec{p}_1 + \vec{p}_2)$
- If $\vec{q}_1$ and $\vec{q}_2$ are obtainable,

$$m_{\tilde{\ell}}^2 \geq max\{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \}$$

- But $\not{E}_T = \vec{q}_1 + \vec{q}_2 \longrightarrow$ the best we can say is that

$$m_{\tilde{l}}^2 \geq m_{T2}^2 \equiv \min_{\not{q}_1 + \not{q}_2 = \not{E}_T} \left[\max \{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \} \right]$$

What if there are two missing particles?: m_{T2}

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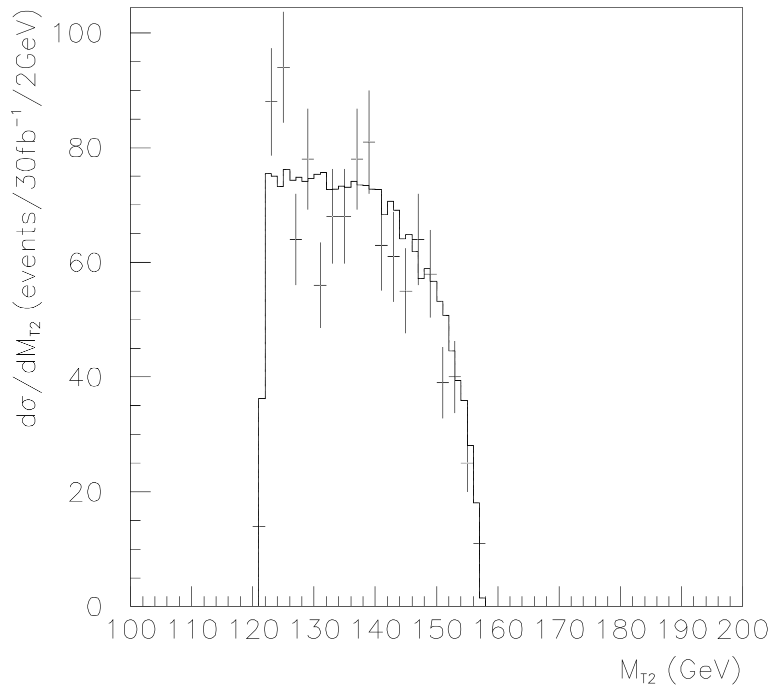
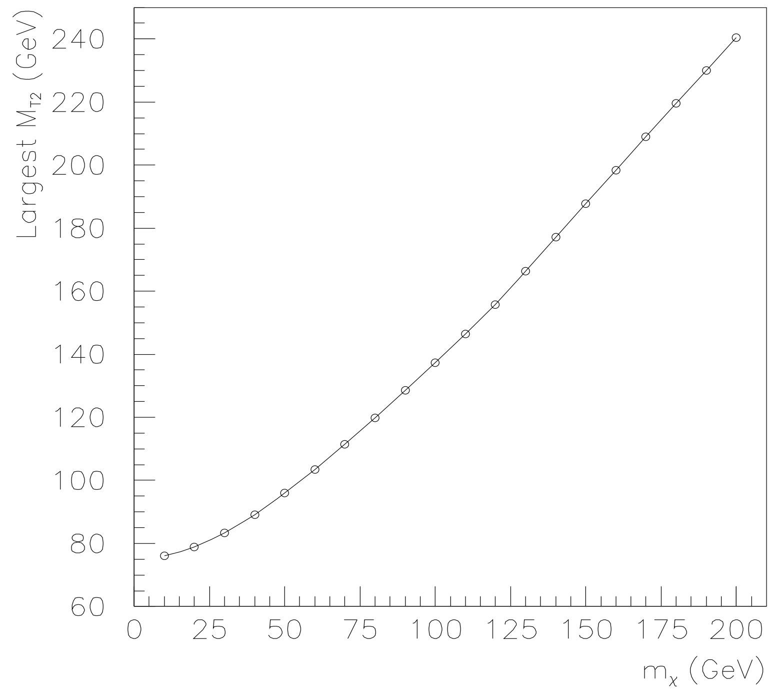


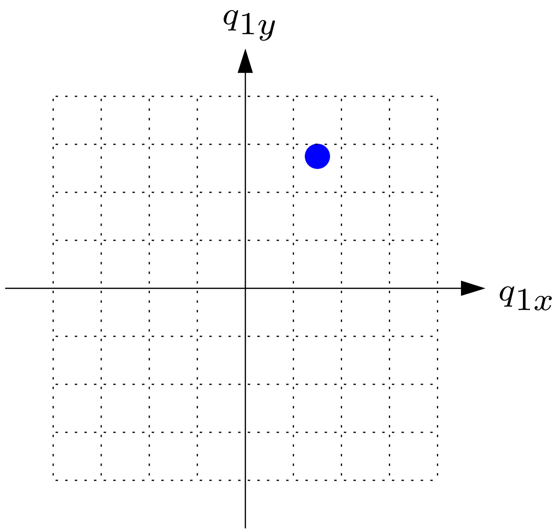


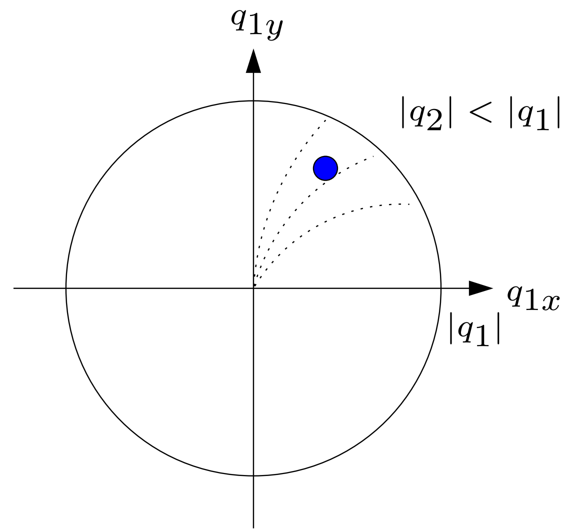
$$m_{\tilde{l}}^2 \geq m_{T2}^2 \equiv \min_{\not{q}_1+\not{q}_2=\not{E}_T} \left[\max\left\{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \right\} \right] \geq m_{\tilde{\chi}_1^0}^2$$

- Rely on momentum scan $\longrightarrow$ can be reduced to one dimensional parameter scan
  $\longrightarrow$ can not get analytic differential distribution
- Have to assume $m_{\tilde{\chi}_1^0}$ $\longrightarrow$ correlation between $m_{\tilde{l}}$ and $m_{\tilde{\chi}_1^0}$

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)





- good: uniform scan
- bad: how far should we scan?

  $0 \leq |q_{1x}|, |q_{1y}| \leq \#|p_1|$

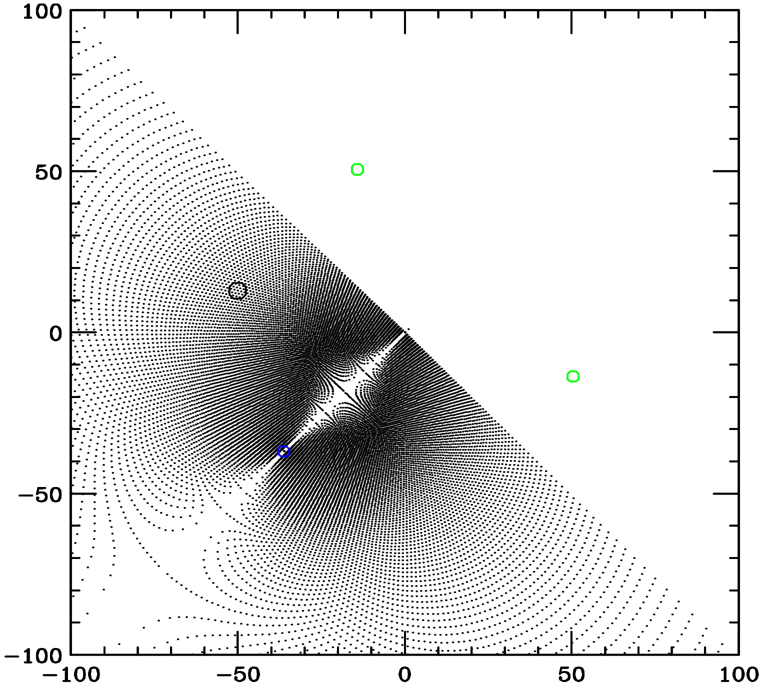
- bad: non-uniform scan
- good: compact scan

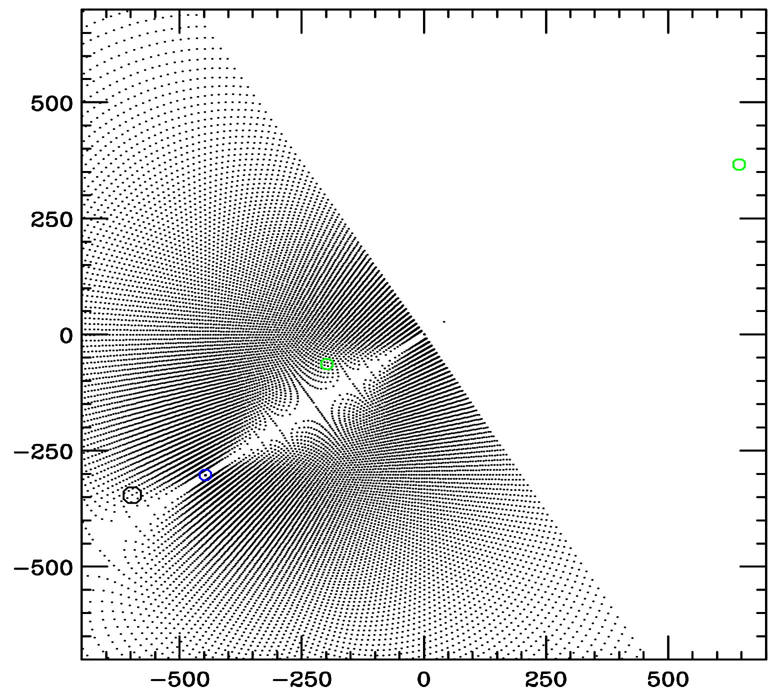
  $|q_2| \leq |q_1|, \; 0 \leq \theta_2 \leq 2\pi$

- $\vec{q}_1 + \vec{q}_2 = \vec{\not{E}}_T$

The Cambridge m_{T2} Variable Demystified

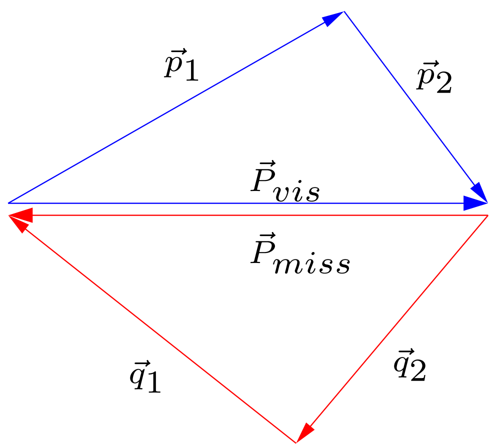
(Kong, Matchev, Preliminary)





The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)



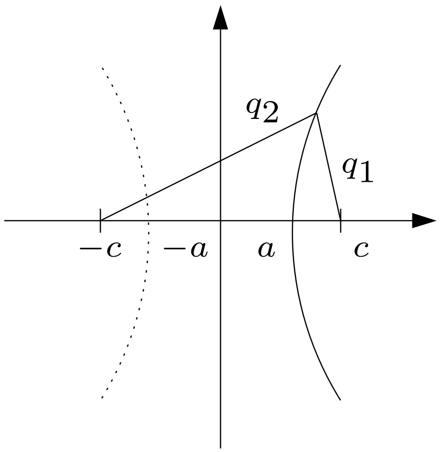
$$m_{T2}^2 \equiv \min_{\not{q}_1 + \not{q}_2 = \not{E}_T} \left[\max \{ m_T^2(\vec{p}_1, \vec{q}_1), m_T^2(\vec{p}_2, \vec{q}_2) \} \right]$$

Constraint: $m_T^2(\vec{p}_1, \vec{q}_1) = m_T^2(\vec{p}_2, \vec{q}_2)$

$$\rightarrow \sqrt{\vec{q}_2^{\,2} + m^2} - \sqrt{\vec{q}_1^{\,2} + m^2} = |\vec{p}_1| - |\vec{p}_2| > 0$$

- massless case ($m = 0$): WW production, $m_{\tilde{\chi}_1^0} << m_{\tilde{\ell}}$

$$2a \equiv p_1 - p_2 = q_2 - q_1$$
$$2c \equiv \not{E}_T$$
$$e = \frac{c}{a}$$



- Solution: $\vec{q}_1 = -\vec{p}_2$ and $\vec{q}_2 = -\vec{p}_1$

- Warning: $\vec{q}_1$ and $\vec{q}_2$ are NOT neutrino momenta

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)

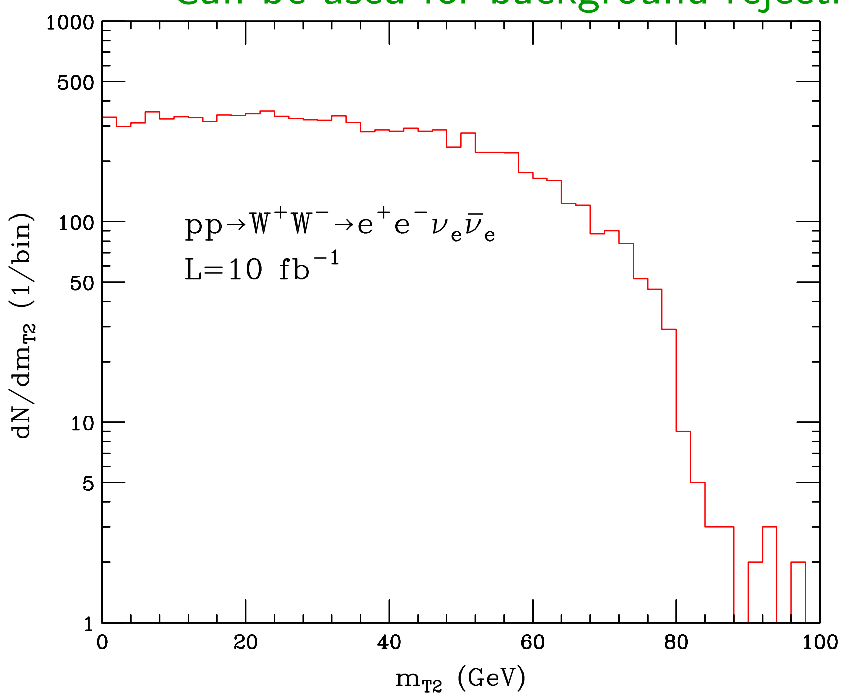
- massive case $(m \neq 0)$

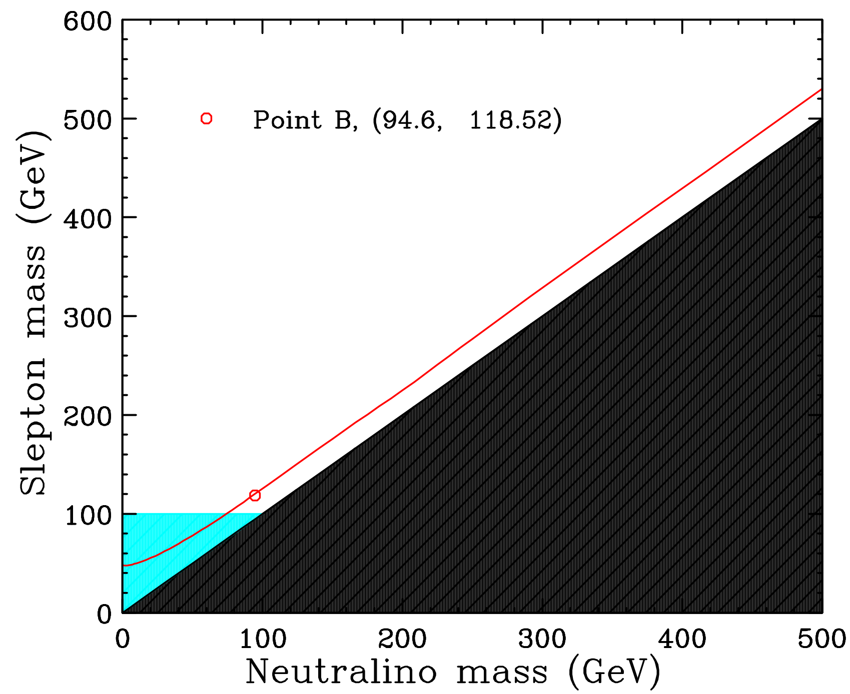
$$
\begin{aligned}
num &= 16\,e\left(1+\left(-1+e^2\right)\mu^2\right)^{\frac{3}{2}}\left(e+\cos(\phi)\right)\left(1+e\,\cos(\phi)\right)\sin(\phi)^2 \\
&+ 4\left(1+\left(-1+e^2\right)\mu^2\right)\left(-2\left(1+e^2+e^4\right)-\left(-1+e\right)\left(1+e\right)\left(2+e^4\right)\mu^2\right. \\
&- \left.4\,e\left(1+e^2+\left(-1+e^2\right)\mu^2\right)\cos(\phi)+e^2\left(-2+\left(2-3\,e^2+e^4\right)\mu^2\right)\cos(2\,\phi)\right)\sin(\phi)^2 \\
den &= -8\left(1+4\,e^2+e^4\right)-4\left(2+e^2\right)\left(-2-5\,e^2+2\,e^4\right)\mu^2+\left(-8-16\,e^2-12\,e^4+4\,e^6-3\,e^8\right)\mu^4 \\
&- 8\,e\left(4\left(-1+\mu^2\right)^2+2\,e^2\left(2-3\,\mu^2+\mu^4\right)+e^4\left(\mu^2+\mu^4\right)\right)\cos(\phi) \\
&+ 4\,e^2\left(-4+2\left(6+e^2+e^4\right)\mu^2+\left(-8+2\,e^2-2\,e^4+e^6\right)\mu^4\right)\cos(2\,\phi) \\
&+ e^3\,\mu^2\left(8\left(2+e^2+\left(-2+e^2\right)\mu^2\right)\cos(3\,\phi)+e\left(4-\left(-2+e^2\right)^2\mu^2\right)\cos(4\,\phi)\right)^4 \\
\sin^2\theta &= \frac{num}{den}
\end{aligned}
$$

The Cambridge m_{T2} Variable Demystified

(Kong, Matchev, Preliminary)

- Applications:
  - Mass correlation even if there are two missing particles:
    W and slepton pair production
  - Can be used for background rejection



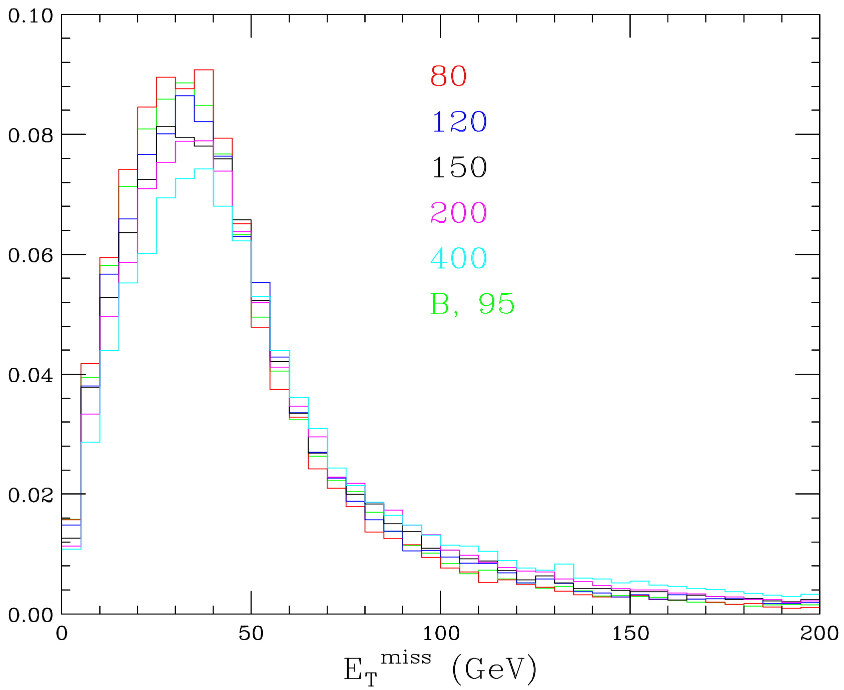


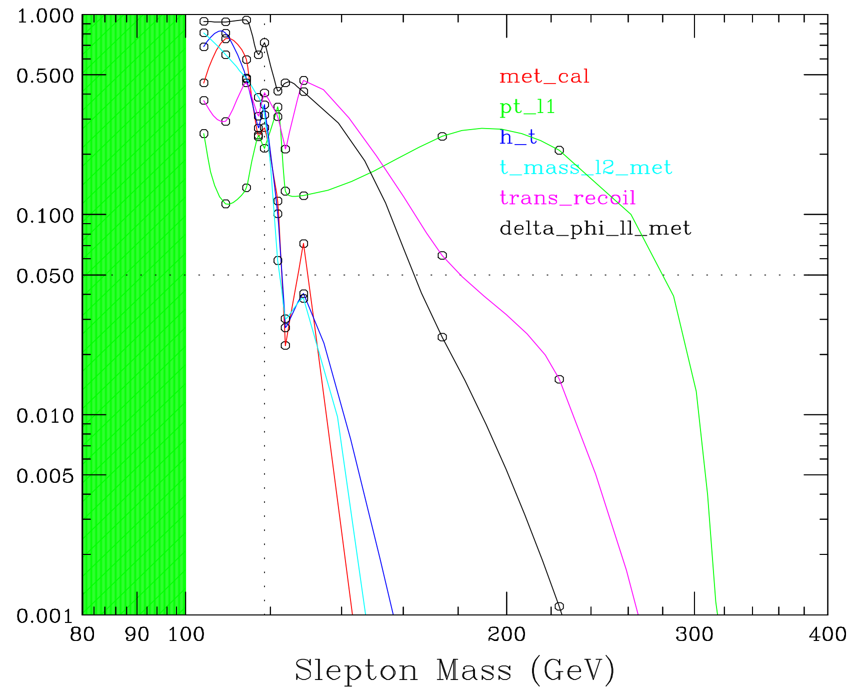
- $N = \sigma \times BR \times \mathcal{L} \times \epsilon =$ fixed
  - $\sigma > \sigma_0(BR = 1) \to m < m_0$

Kolmogorov-Smirnov Test

(Kong, Matchev, Preliminary)

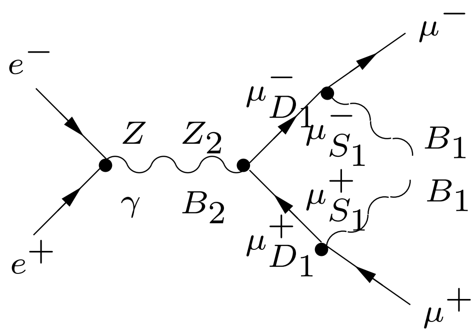
- Is there another mass measurement?
- KS test?

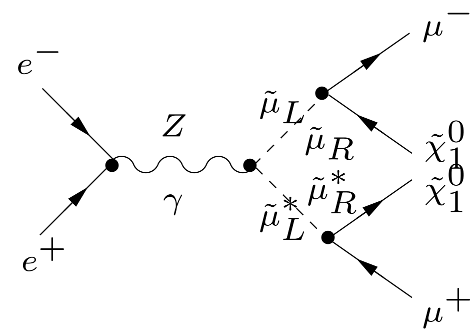




- Difficulties:
  - Not enough statistics
  - Cuts distort shapes of the distributions

SUSY vs UED at LC in $\mu^+\mu^- + \not{E}_T$ channel





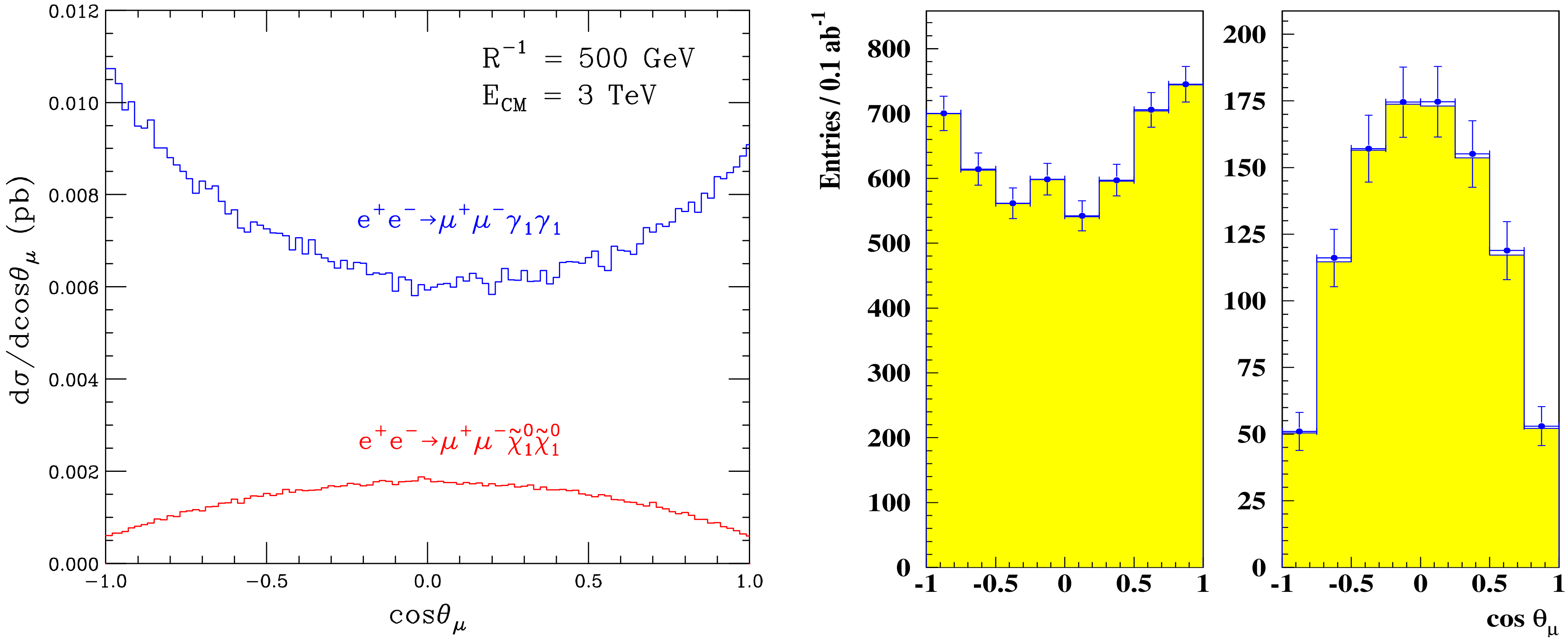
- Angular distribution

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \frac{E^2_{\mu_1} - M^2_{\mu_1}}{E^2_{\mu_1} + M^2_{\mu_1}} \cos^2\theta \qquad \left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$$
$$\sim 1 + \cos^2\theta$$

- μ^- energy distribution
- Threshold scan
- Photon energy distribution

The Angular Distribution (LC)

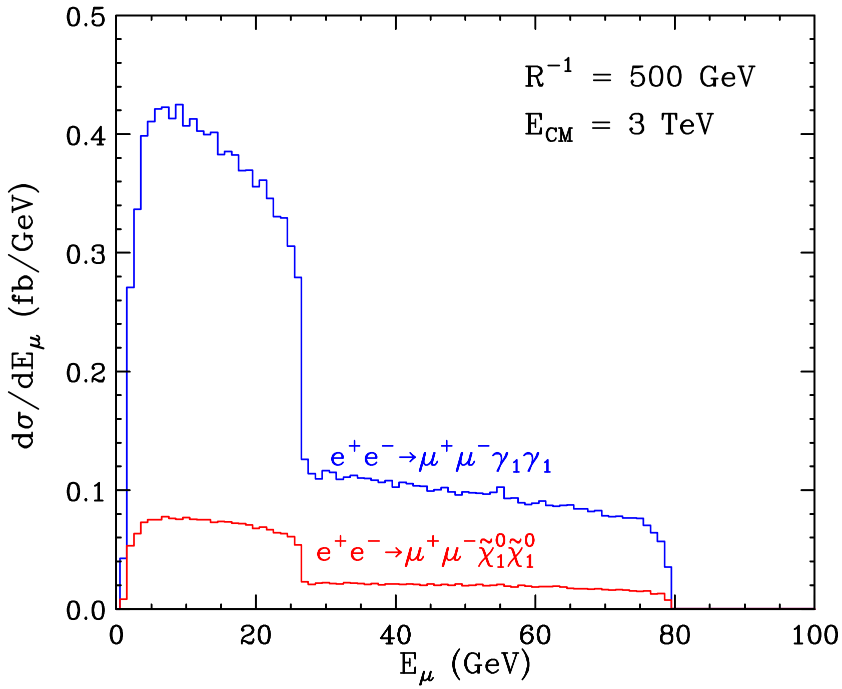
(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)

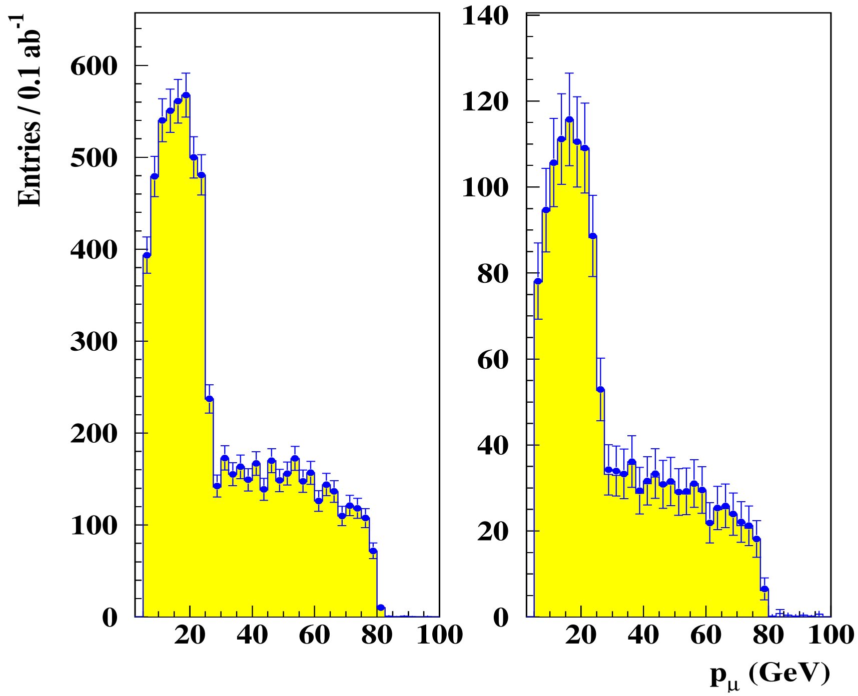


- $\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \cos^2\theta$
- $\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$

The μ Energy Distribution (LC)

(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)

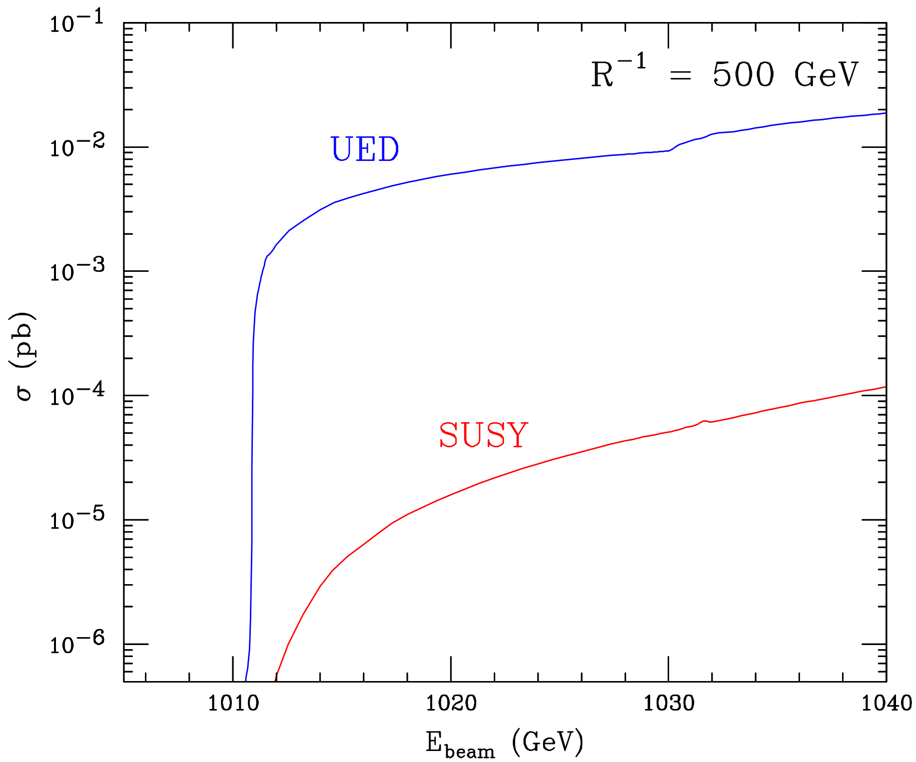




- $E_{max/min} = \frac{1}{2} M_{\mu^*} \left(1 - \frac{M_N^2}{M_{\mu^*}^2}\right) \gamma(1 \pm \beta)$
  - M_{μ^*} : mass of smuon or KK muon
  - M_N : LSP or LKP mass
  - $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ with $\beta = \sqrt{1 - M_{\mu^*}^2/E_{beam}^2}$ (μ^* boost)

Threshold scans (LC)

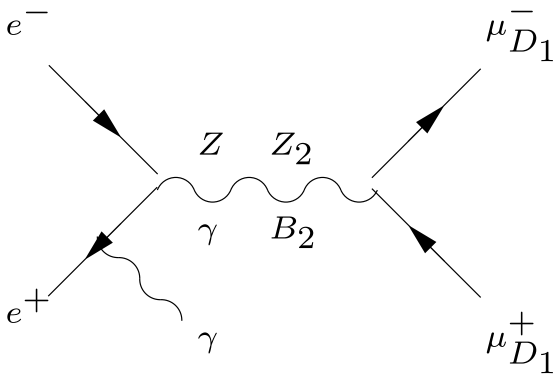
(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)

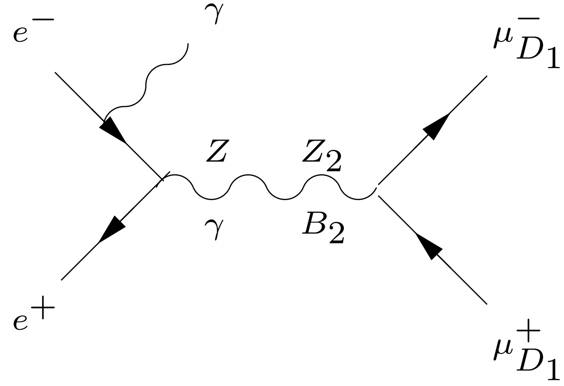


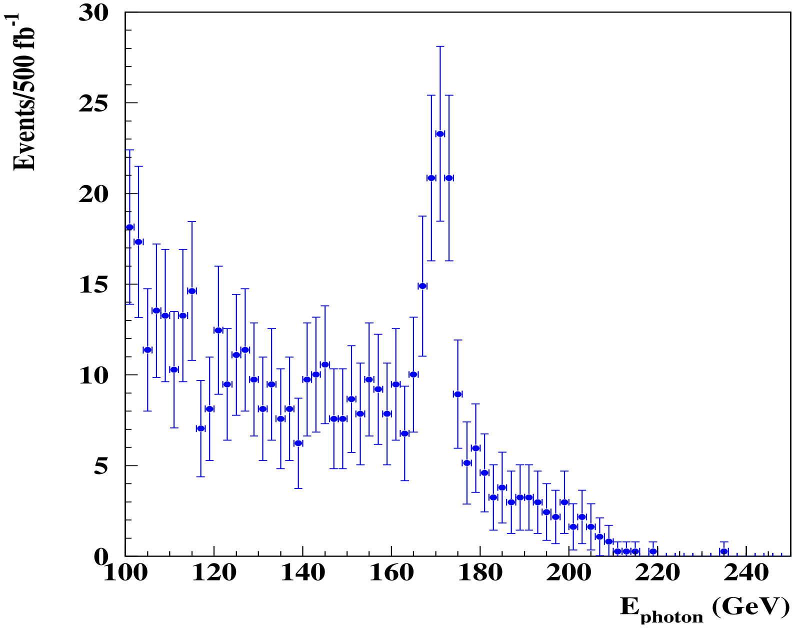
- Mass determination
- Cross section at threshold
  - in UED $\propto \beta$
  - in MSSM $\propto \beta^3$ $\left(\beta = \sqrt{1 - \frac{M^2}{E^2_{beam}}}\right)$

The Photon Energy Distribution (LC)

(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)



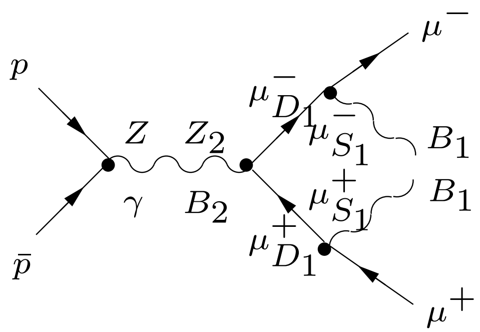


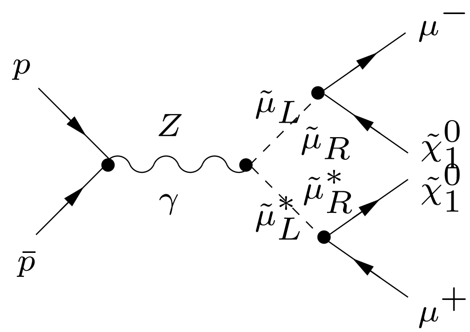


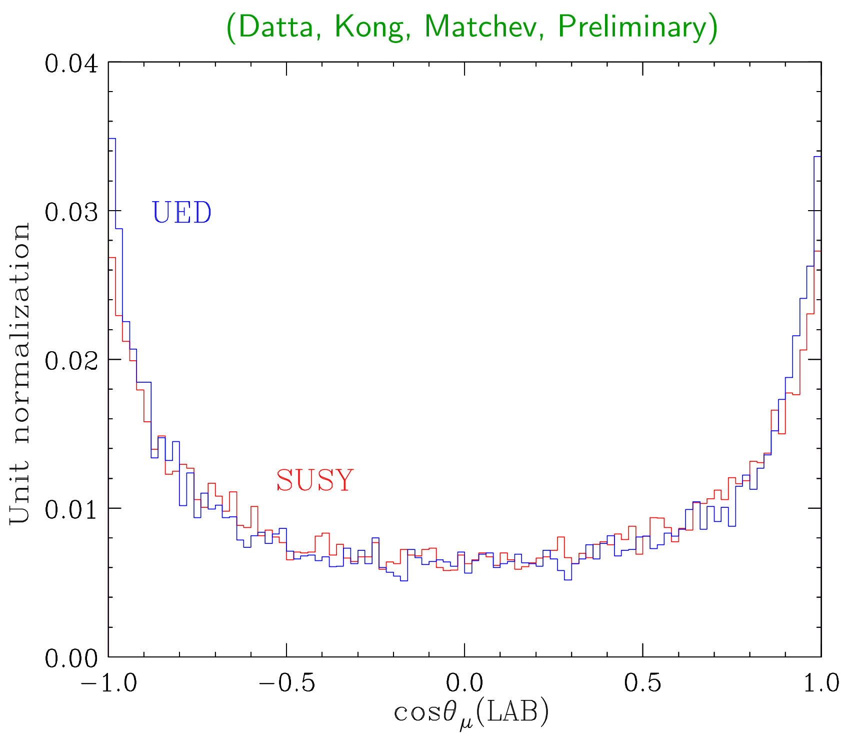
- Smuon production is mediated by γ and Z
- On-shell $Z_2 \to \mu_1 \bar{\mu}_1$ is allowed by phase space
- Radiative return due to Z_2 pole at

$$E_\gamma = \frac{s - M_{Z_2}^2}{2\sqrt{s}}$$

The Angular Distribution at the LHC







- If we simply do the same trick as in linear collider, it doesn't work
- There is no fixed CM frame

Exact Beamstrahlung Function Required

- Analytic solutions are limited for small Υ only
  - Good agreement with simulation data
  - This is true for LC 500-1000
- Can't use same solution for large Υ
  - Need new approximation $\longrightarrow$ No analytic solution for large Υ in the case of high energy e^+e^- colliders such as CLIC
  - Solve rate equation numerically instead or
  - Use simulation data
- Caution : Implementation in event generators
  - Most event generators have one of these two parametrizations
  - Either numerically worse or has normalization problem
  - How to fix the event generator
    - Use old parametrizations and fake parameters
    - Use numerical solution/simulation data and import in the event generator
- A lot of soft photons at high energy e^+e^- colliders distort physical distributions, e.g. E_μ

Summary

- LHC is finally coming
- New physics beyond the SM is expected to be discovered but will we know what it is?
- Many candidates for new physics have similar signatures at the LHC (SUSY, UEDs, T-parity...).
- Crucial to know spin information of new particles.
- Important to know mass spectrum.
- Need to develop new methods: m_{T2}...
- Issues at LC: beamstrahlung ...